Development of left-handed composite materials and negative refracting photonic crystals with subwavelength focusing

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We review the studies conducted in our group concerning electromagnetic properties of metamaterials and photonic crystals with negative effective index of refraction. In particular, we demonstrate the true left handed behavior of a 2D composite metamaterial by analyzing the electric and magnetic response of the material components systematically. The negative refraction, subwavelength focusing, and flat lens phenomena using 2D dielectric photonic crystals are also presented.

Periodic Effective Medium Description of LHM

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When the wavelength inside a periodically structured Left Handed Material (LHM) becomes comparable to or larger than the characteristic length(the period) of the LHM its description as a uniform homogeneous effective medium breaks down. In this case it is still possible to employ a periodic medium consisting of alternating layers of a properly chosen dielectric of constant permittivity and a uniform homogeneous LHM. This scheme extends the validity of the effective medium concept well beyond its homogeneous version.

Sub-wavelength RF imaging with magnetic metamaterials

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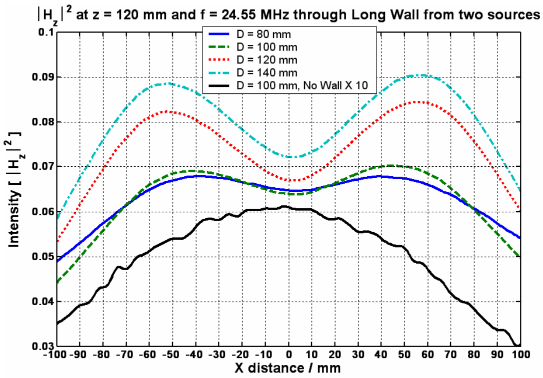
Materials with negative refractive index can focus both the propagating and the evanescent fields, thus giving the potential for sub-wavelength imaging. In the extreme near field, the electric and magnetic fields are independent, so a negative permeability, μ, is sufficient to focus magnetic fields. We have constructed a 60 mm thick, 2-dimensional isotropic wall, of “Swiss Rolls”, a magnetic metamaterial tuned to operate with $\mu = -1$ near 25 MHz, where the wavelength of electromagnetic radiation in free space is ~12 m. We placed two collinear magnetic sources, spaced between 80 and 140 mm apart, behind the wall, and measured the intensity of the magnetic field in the “image” plane, 120 mm away from the sources. Without the wall, no structure is observed, but, when the wall is present, we find two peaks, whose separation varies with that of the sources, thus demonstrating an imaging resolution of $\lambda/100$.



$\lambda/100$ Imaging at 24.55 MHz

Ferromagnetic-metal nanocomposite films as a possible candidate for left-handed materials

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Recently, a novel route to materials with both permittivity and permeability negative, called left-handed materials (LHMs), in the region of microwaves using ferromagnetic-metal nanocomposites has been proposed [1]. In this study, we prepared nanocomposite films consisting of metallic Ni nanoparticles several nanometers in diameter embedded in polymer matrices. It was found that diameter and volume fraction of the Ni particles can be controlled independently and precisely. These structural parameters strongly affected the electron magnetic resonance condition of the films. This suggests that the control of the film structures is important to tune the frequency where the LHMs may be obtained in this route.

[1] S.T. Chui and L. Hu, *Phys.Rev.B*, **65**, 144407 (2002).

Towards Left-handed Metamaterials at Optical Frequencies

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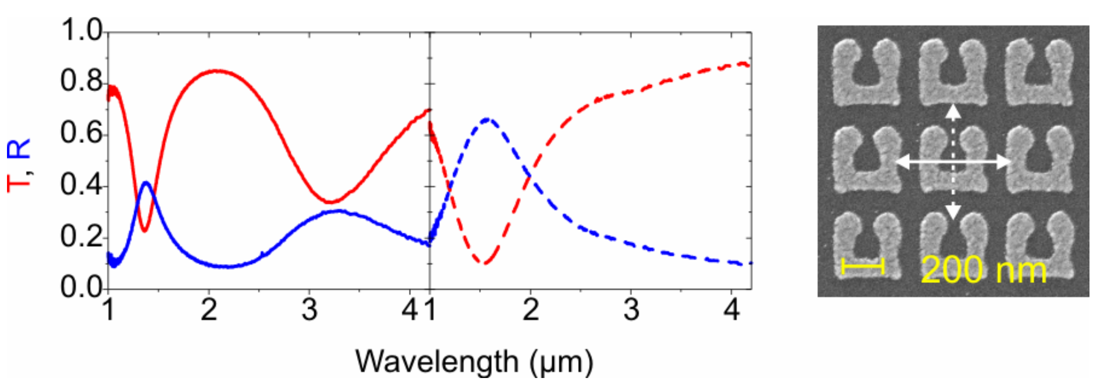
Metamaterials allow for optical properties not available from natural materials. An important application are left-handed metamaterials which exhibit a negative index of refraction. A prerequisite for this unusual property is that the effective permittivity ε and the effective permeability μ are both negative. While a negative ε is not unusual, a large magnetic response, in general, and a negative μ at optical frequencies, in particular, does not occur in natural materials. In metamaterials, this crucial aspect is achieved by mimicking an LC-oscillator, consisting of a magnetic coil and a capacitor. Such metamaterials were first realized at frequencies around 10 GHz (3-cm wavelengths) [1]. Using nanofabrication techniques, we increase the LC-resonance frequency to about 100 THz (3-μm wavelength) [2], bringing a negative index of refraction at optical frequencies into reach. Transmission (T) and reflection (R) spectra for two orthogonal linear polarizations (as indicated in the SEM image) are shown below. For normal incidence, coupling to the LC resonance is only possible if the electric field has a component normal to the plates of the capacitance (LHS). The features around 3-μm wavelength correspond to the LC-resonance. The resonance completely disappears if the electric field vector is rotated by 90° (RHS). The plasmon resonance at 1.5-μm wavelength can be excited in both configurations [2]. More recently, we have achieved a magnetic response at telecommunication wavelengths.



[1] R. A. Shelby et al., *Science*, **292**, 77 (2001).
[2] S. Linden et al., *Science*, **303**, 1494 (2004).

Infrared spectroscopy and ellipsometry of magnetic metamaterials

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We present S and P polarized measurements of artificial bianisotropic magnetic metamaterials with resonant behavior at infrared frequencies.[1] These metamaterials consist of an array of micron sized (~40μm) copper rings fabricated upon a quartz substrate. Simulation of the reflectance is obtained through a combination of electromagnetic Eigenmode simulation and Jones matrix analysis, and we find excellent agreement with the experimental data. It is shown that although the artificial magnetic materials do indeed exhibit a magnetic response, care must be taken to avoid an undesirable electric dipole resonance, due to lack of reflection symmetry in one orientation. The effects of bianisotropy on negative index are detailed and shown to be beneficial for certain configurations of the material parameters.

[1] W.J. Padilla, et al., *Science*, **303**, 1494 (2004).

Negative Refraction Metamaterials in Optics

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An array of pairs of parallel gold nanorods can form a metamaterial with a negative refractive index in the optical range. Such behavior results from the plasmon resonance in the pairs of nanorods for both the electric and magnetic components of light. The metal rods act as inductive elements whereas the dielectric gaps perform as capacitive elements, forming an optical LC-circuit. Our experiments and simulations demonstrate the resonant behavior for the index of refraction. Above the resonance, the refractive index becomes negative. Paired metal nanorods open new opportunities for developing negative-refraction materials in optics.

On possible realizations of backward-wave regime and negative refraction in chiral composites

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It is well known that negative refraction happens at an interface between a usual isotropic medium (vacuum, for example) and a material with negative parameters (called Veselago medium, double-negative material, or backward-wave medium). However, recent studies have shown that backward waves can propagate in materials with positive parameters provided one of the materials is *chiral* (S. Tretyakov, I. Nefedov, A. Sihvola, S. Maslovski, C.Simovski, Waves and energy in chiral nihility, *J. Electromagn. Waves Applic.,* vol. 17, no. 5, pp. 695-706, 2003; J. Pendry, A Chiral route to negative refraction, *Science,* vol. 306, pp. 1353-1955, 2004; H. Dakhcha, O. Ouchetto, S. Zouhdi, Chirality effects on metamaterial slabs, Proc. of *Bianisotropics'2004 - 10th Conference on Complex Media and Metamaterials,* pp. 132-135, Ghent, Belgium, September 22-24, 2004).

The physics of the effect is very simple: The propagation constants of two eigenwaves in isotropic chiral media equal $\beta = (n \pm \kappa)k_0$, where $n = \sqrt{\varepsilon\mu}$ is the usual refractive index, κ is the chirality parameter, and k_0 is the free-space wavenumber. Near a resonance of the inclusions forming the material the real part of the refractive index *n* can become smaller than the real part of the chirality parameter κ. It means that one of the two eigenwaves is a backward wave, because its phase velocity is negative but the energy transport velocity is positive. At an interface between a usual isotropic material and such medium negative refraction takes place for this polarization (waves of the other polarization refract positively). This is a very exciting new opportunity to realize negative refraction and related effects in the optical region in effectively uniform media (the characteristic dimensions in the material can be much smaller than the wavelength).

To realize the effect, Pendry (*Science*, 2004) proposed to use a double-phase composite, embedding resonant dielectric phase in a chiral background. Tretyakov et al. *(JEWA*, 2003) proposed to utilize the resonant regime of a single-phase chiral material, for instance, made of helical-shaped inclusions. In this presentation, we will give an overview of backward-wave regime in chiral media and discuss how such regimes can be practically realized using both proposed scenarios. Numerical estimations for the frequency dependence of material parameters near the appropriate resonances will be shown. We will demonstrate that resonant behaviour of background permittivity (as in the design of Pendry) very strongly influences the effective chirality parameter, which can make it very difficult to achieve the desired effect.